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Performance of large fan-filter units for cleanroom applications

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Abstract

Fan-filter units (FFUs) are widely used in clean space to re-circulate and remove particles out of the airflows directed to cleanrooms or minienvironments. Energy and aerodynamic performance of FFUs may largely influence both energy efficiency and effectiveness in contamination control in the cleanroom design, qualifications, and operation. This article presents laboratory-measured performance of seven relatively new and large FFUs, with a section size of 122-cm × 122-cm, or 4-ft × 4-ft. In addition, this article includes a comparison of the performance of these large FFUs with that of smaller, 122-cm × 61-cm (or 4-ft × 2-ft) FFUs that were previously tested. The comparison was based upon a set of performance metrics such as total pressure efficiency (TPE) and energy performance index (EPI). This article found that there were wide variations in the energy performance of FFUs, and that using a consistent evaluation method can generate comparable FFU performance information. When operating at the maximal setting of speed control dials used to control their respective fan-wheel speeds, the larger units in this study tended to be more energy efficient than their smaller counterparts. The energy efficiency level of the same unit may vary considerably, depending on actual operating conditions such as airflow speeds and pressure rise across the units. Furthermore, this article provides recommendations for further investigations to improve energy efficiency of FFU applications.

Keywords: Cleanroom; Fan-filter unit (FFU); Airflow; Energy efficiency; Total pressure efficiency (TPE); Energy performance index (EPI)

1. Introduction

Cleanroom HVAC systems represent a large fraction of energy use in cleanrooms. Recent studies have found that the performance of HVAC systems varies significantly from cleanroom to cleanroom because of various, and often, complex factors [1,2]. Such underlying factors include, but are not limited to, requirements for contamination control, design of air-recirculation systems, layout and system resistance of HVAC systems, effectiveness of particle-removal rates, and the energy efficiency of air-system components. Previous studies [2–5] addressed energy-saving opportunities in cleanroom applications, one of which was to optimize energy performance in air-recirculation systems.

An FFU is a self-contained unit normally attached to cleanroom T-bar ceilings and is used to supply and clean airflows, which are fed to and then re-circulated through the cleanroom space. The FFU achieves effective contamination control in the cleanroom by providing certain particle filtration and recirculation-air-change rates for a specified space. An FFU usually consists of a small fan, a controller, and a high-efficiency-particulate-air (HEPA) filter or an ultra-low-penetration-air (ULPA) filter enclosed in a box, which fits into common cleanroom ceiling grids. In recent years air-recirculation systems adopting fan-filter units (FFUs) are increasingly gaining popularity worldwide. This phenomenon is being driven by the needs for specific contamination control, ease of installation, and adaptability in cleanroom construction, qualification, and operation. Common ceiling grids typically carry FFUs with unit sizes ranging from 122-cm × 122-cm (4-ft × 4-ft) down to 122-cm × 61-cm (4-ft × 2-ft) or smaller. The small fans inside the FFUs force air through the HEPA or ULPA

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filters and for an entire cleanroom. The FFU coverage in a cleanroom ceiling normally ranges from 25% to 100% of the total ceiling area in a cleanroom, which requires a large number of FFUs. As a result, the large number of small fans in FFUs constitutes considerable electric power demand and energy use in providing air recirculation and cleaning.

While FFUs are becoming more popular, their energy and aerodynamic performance could be different even with similar components. To achieve sustainable development in cleanroom facilities, it is useful for designers and owners to have comparable information on FFU energy performance. This makes it feasible to select efficient units and to improve energy efficiency while maintaining or improving the effectiveness in contamination control. Unfortunately typical manufacturers datasheets usually contain numbers that look similar but not readily comparable. This is due to the fact that their approaches to reporting performance data are different from each other, and often misleading. For example, an FFU label containing specification of "120-Watts, 55-dBA, 90-fpm (or 0.45-m/s)" conveys vague information because it does not specify what "90-fpm (or 0.45-m/s)" really refers to, nor is the condition under which the labeled information was obtained. Such ambiguity may lead to various interpretations, such as the airflow speed at the room cross-section, across the net HEPA or ULPA filter media, at the face of the HEPA or ULPA filter, or at an unspecified distance from the HEPA or ULPA filter exit. As a result, suppliers' data information cannot be meaningfully compared or its usefulness is, at most, immaterial.

Lawrence Berkeley National Laboratory (LBNL) and Industrial Technology Research Institute (ITRI) of Taiwan are investigating laboratory methods to consistently test FFU energy and aerodynamic performance [6–8]. Based upon the investigations, we intended to generate data for performance comparison and to identify areas of improvement in the units' energy performance.

2. Objectives

The objectives of this paper are to (1) present laboratory testing results on aerodynamic and energy performance of seven FFUs with the size of 122-cm × 122-cm, or 4-ft × 4-ft; and (2) compare the performance of seven sample FFUs with that of the smaller FFUs (122-cm × 61-cm, or 4-ft × 2-ft) that was recently published [8–10]. This paper presents the testing results of large FFUs and evaluates their energy performance when the speed control dial used for adjusting fan-wheel speeds in each FFU was set at its maximum.

3. Approaches

In this study, the individual 122-cm × 122-cm FFUs were connected with an inlet chamber setup consistent with a test method to determine a fan's aerodynamic performance [7]. The chamber contained a multiple-nozzle bank for recording airflow rates through the tested unit. The air from the mediate downstream of the FFUs was discharged to the atmosphere. A booster fan and a damper were installed at the chamber inlet to modulate air pressures inside the chamber so that the airflow rates and pressure rise across the FFUs were controlled. Fig. 1 shows the basic measurement layout.

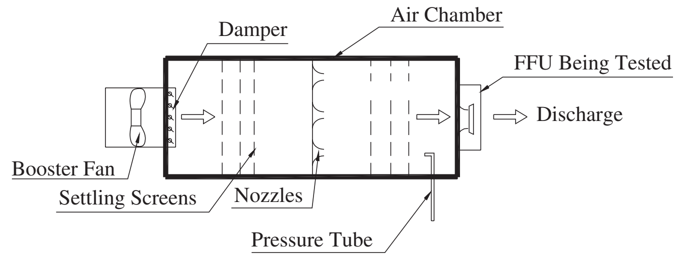

Fig. 1. Laboratory measurement layout.

The FFUs tested were mounted vertically on the exit end of the air chamber. Exit airflow of the FFU discharged into a room with the air at atmospheric conditions. The HEPA or ULPA filter was considered an integral part of each FFU in this study. The total pressure is the sum of the static pressure and the dynamic pressure at a certain location of the airflow path. The total pressure rise across the FFU is measured within the chamber using the FFU exit location as the base (Fig. 1). It represents the "pressure gain" as the air flows through the unit, where the fan impeller exerts energy on the airflow. The FFU pressure rise across the unit therefore represented the unit's capability to overcome the airflow resistance in the recirculation air system so that the pressure at the HEPA or ULPA filter exit is not less than the ambient pressure. Static pressures at the inlet of each FFU were modulated by adjusting damper positions in order to generate a performance curve covering the range of operable conditions. Each FFU was tested with its speed modulation device set at its maximum dial-setting position for the fan wheel. The ambient conditions and the airflow conditions were recorded and were used for conversion to the equivalent standard condition, namely, one standard atm, 20 °C, and air density of 1.20 kg/m^3, for direct comparisons.

This article focuses on energy and aerodynamics performance of the units and identify areas of further improvement to the testing method and opportunities for energy efficiency. Other performance metrics such as acoustic, vibration, filter efficiency, filter media for controlling airborne molecular contamination, outlet flow uniformity, and in situ performance, are addressed to various extents, in relevant literatures including standards, certification documents, or recommended practices [11–13].

4. Laboratory measurements and metrics

Based on the measured data, we performed data analysis to quantify a group of metrics at various operating conditions developed from the tests. The metrics were recently developed to evaluate energy and aerodynamic performance [10], which allowed direct comparison of the performance of these large FFUs with that of the smaller ones.

One of the examples in examining energy performance of FFUs is to quantify the total pressure efficiency (TPE), and electricity power demand (input) per airflow rate under certain operating pressures. These metrics can be used by designers or owners in their life-cycle-cost analysis when needed. They can also be used to formulate energy-efficiency criteria for use in electric utility incentive programs. The following defines the key metrics used in this paper:

(1) Airflow Speed: Unit airflow rate divided by the net FFU face area under a specific static pressure. Expressed in m/s, or foot per minute (fpm).
(2) TPE: Ratio of total pressure power to total actual power demand for an FFU. The total pressure power is obtained by multiplying the airflow rates with the total pressure rise across the unit; expressed in percentage.
(3) Energy Performance Index (EPI): Unit's total power demand normalized by the airflow rate through the FFU under certain conditions. Expressed in Watt per m^3/min, or Watt per cubic foot per minute (cfm), i.e., W/cfm.

A power meter measured actual power input of an FFU with the measurement uncertainty within $\pm 0.5\%$. The uncertainty in the airflow and pressure measurements is within $\pm 2.5\%$. With the magnitudes of airflow speeds in the order of 0.50 m/s (or about 100 fpm) or less, dynamic pressures of airflows through FFUs are usually less than 0.2 Pa. If we consider that pressure resistance in the recirculation-air system is around 50–100 Pa and that static pressure rise across the units could be higher than 50 Pa, dynamic pressures of airflows with speeds of 0.50 m/s or lower would only account for an insignificant fraction ($<0.4\%$) of the total pressures. In this article, values of static pressures or total pressures across the units are expressed interchangeably.

5. Results and comparisons

This paper evaluates the energy and aerodynamic performance of seven large FFUs (122-cm × 122-cm, or 4-ft × 4-ft) that were tested in calibrated laboratory setting [7]. These FFUs were made by various suppliers located in Asia, Europe, and North America. Each of the FFUs tested has backward inclined centrifugal impellers. All of the samples used single-phase or three-phase AC power supply.

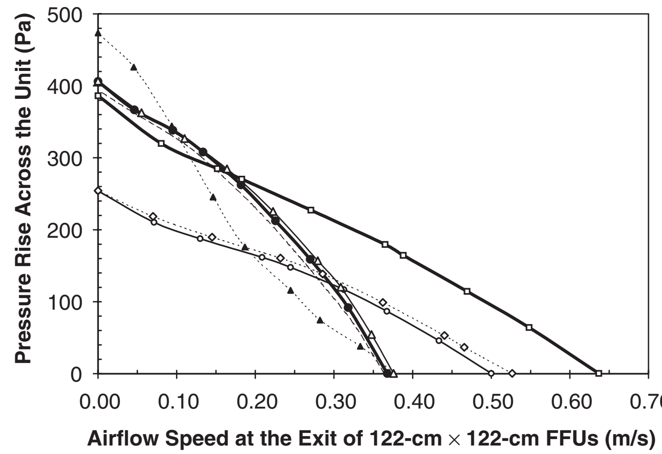

Fig. 2. Pressure rise across the unit and airflow speed at FFU exit.

5.1. Pressure rise across unit

Fig. 2 shows the curves of the pressure rise across the 122-cm × 122-cm units as it related to the actual airflow speeds at the FFU exit. Each line represents the operable ranges for each of the FFUs when the speed control dial used for adjusting fan-wheel speeds in each FFU was set at its maximum.

For a typical cleanroom system resistance of 125 Pa (or about 0.5 in water), most of the FFUs would operate at airflow speeds typically ranging from 0.25 to 0.50 m/s (or about 50–100 fpm). This exhibited a similar trend to those of the smaller, 122-cm × 61-cm units reported in a previous study [9]. For the majority of the 122-cm × 122-cm units (five out of seven), the maximal airflow speed in this study was however lower than 0.40 m/s (80 fpm).

The figure indicates that an increase in airflow speeds corresponded consistently with the decrease in pressure rise across the unit—it corresponded to reduced static pressure (and total pressure) as a result of wider opening of the damper coupling with the original fan features.

5.2. Total pressure efficiency

The TPE is the actual airflow's total pressure power divided by the total electric power input to the FFU unit (Eq. (1)). Airflow total pressure power is to move air through the FFU at certain airflow conditions. The total FFU pressure efficiency includes electrical efficiency and mechanical efficiency of the whole FFU unit:

$$\mathrm{TPE} = \Delta P_t Q / P_{\mathrm{elec}}, \tag{1}$$

where ΔP_t is the FFU pressure rise (Pa), Q the airflow rate (m^3/s), and P_{elec} is the total electric power input to FFU (W).

Fig. 3 shows performance curves of individual FFUs in terms of their TPE as a function of airflow speeds at the FFU exit. Each line indicates the efficiency range for each of the FFUs tested when the speed control dial used for

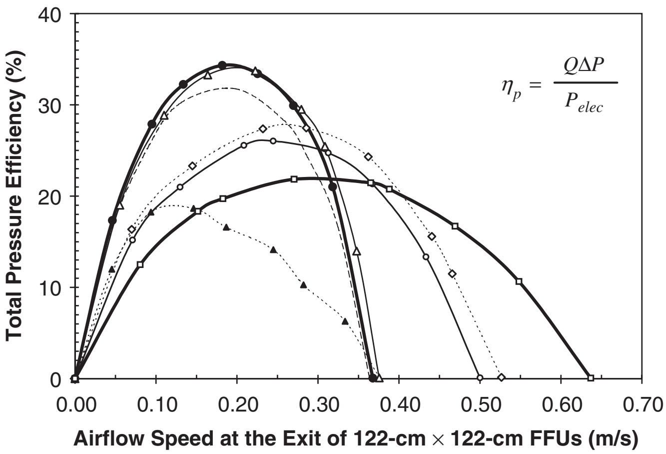

Fig. 3. Total pressure efficiency and airflow speed at FFU exit.

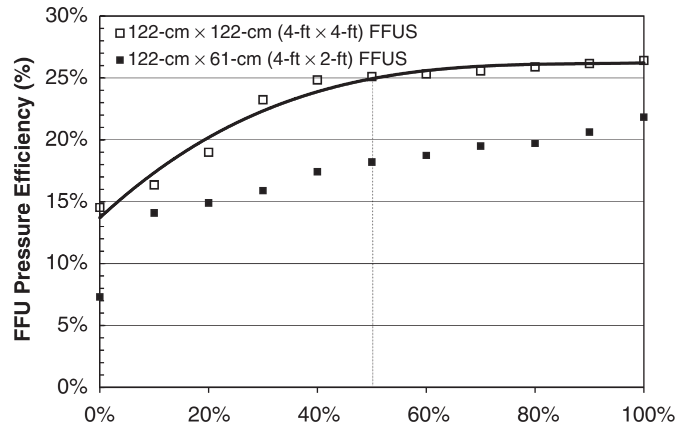

Fig. 4. Comparison of FFUs' pressure efficiency at 125-Pa pressure rise.

adjusting fan-wheel speeds in each FFU was set at its maximum.

It is clear that there was a peak in the TPE as the airflow speed changes progressively from a low rate (e.g., 0.10 m/s) to a higher rate (e.g., 0.30 m/s). TPE of the FFUs varied considerably from unit to unit for the same airflow speed, and exhibited significant variation at different operating airflow speeds, even for the same unit.

The maximal TPE of the FFUs, operating with airflow speeds at or below 0.30 m/s (60 fpm), ranged from 20% to 34% with a median of 28%. This was much higher than the median values of the maximal TPE of smaller units, i.e., 122-cm × 61-cm (or 4-ft × 2-ft) units that were reported in previous studies [8,9]. The majority of the units tested in this study produced airflow speeds within the range of 0.25–0.50 m/s, which were typical in cleanroom applications, at a static pressure of about 125 Pa (or about 0.5 in water). Additionally, the TPE of an individual FFU may deviate away from its peak toward the minimal (e.g., zero) very quickly, corresponding to a relatively narrower range of the airflow speeds.

On the other hand, some of the larger, 122-cm × 122-cm units with lower TPE performed worse than some of the better, smaller 122-cm × 61-cm units [8,9], in terms of energy and aerodynamic performance. This indicates that FFUs with larger sizes alone did not necessarily yield better energy efficiency, and that there were additional factors affecting the actual energy performance of the units beyond the physical size of the unit, motor and fan.

Fig. 4 shows the percentile distribution of the TPE of the seven large (122-cm × 122-cm) units operating at a pressure rise of 125 Pa (0.5 in water), as compared with that of the ten smaller (122-cm × 61-cm) units under the same pressure rise condition. The trend of the curves indicated that at a pressure rise of 125 Pa (or about 0.5 in water), large FFUs, operating within a range of airflow speeds between 0.24 and 0.45 m/s (or about 48–90 fpm), exhibited higher TPE than did the smaller ones. For example, the TPE varied approximately between 15% and 26%, with a median TPE value at 25%. This was higher than previous reported values for smaller FFUs [8–10], which typically operated within 0.30–0.50 m/s—slightly higher airflow speeds.

The energy and aerodynamic performance of the 122-cm × 122-cm (4-ft × 4-ft) units can differ significantly at various operating conditions. Some of the units exhibited an even narrower operating range in terms of airflow speed. This indicates that the performance of these larger units exhibited higher sensitivity to the actual airflow speeds; therefore, it is very critical to specify actual operating range for such units in cleanroom and minienvironment applications.

Compared with the results from the earlier studies, Figs. 3 and 4 indicate some trend of improvement in the aerodynamic performance of these larger FFUs over their smaller counterparts. The trend of improvement probably is due to a combination of factors such as technology improvement of individual FFU components, fan motor efficiency, lower resistance for a same airflow speed, and design enhancement for the units.

By examining the magnitudes of TPE in this study, we can see that the efficiency of one unit could be many times as much as others at a certain condition. Based upon the above analysis, it is clear that there are considerable variations in the FFUs' aerodynamic performance from product to product. It is also clear that there is a potential for some of FFU suppliers to improve FFU aerodynamic performance under certain operating and design conditions.

5.3. Energy performance index

EPI represents the electric power demand required for the FFU to re-circulate a certain airflow rate within the cleanroom recirculation system. EPI indicates the level of electricity power intensity given the same airflow rate. A higher value of EPI indicates higher power intensity, and lower efficiency in delivering the same amount of airflow within certain time.

Fig. 5 shows the trend of EPI values as they corresponded to various airflow speeds. Each line indicates the EPI range for each of the FFUs tested, when the speed

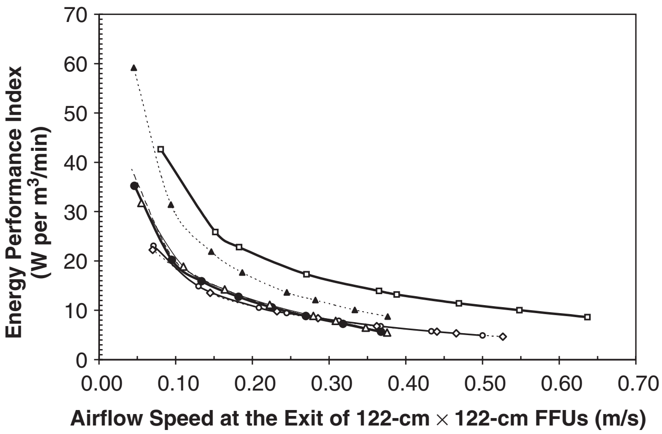

Fig. 5. FFUs' energy performance index at 125-Pa pressure rise.

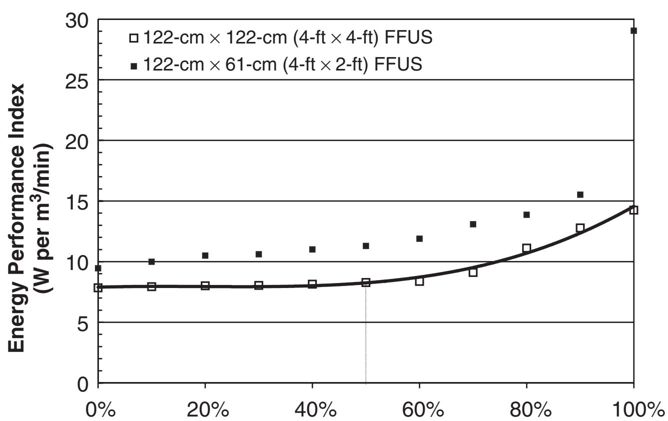

Fig. 6. Comparison of FFUs' EPI at 125-Pa pressure rise.

control dial used for adjusting fan-wheel speeds in each FFU was set at its maximum. Contrast to the observation from Fig. 3 that there was a peak in the TPE as the airflow speed changed progressively from a lower level (e.g., 0.10 m/s) to a higher level (e.g., 0.30 m/s), the EPI values decreased consistently with the increase in airflow speeds for each of the units, as shown in Fig. 5. This trend indicates that the fan inside the FFU, with a wider damper opening to allow higher airflow rates, would not have to work as hard as it would have to, compared to other cases in which the system-resistance increases (e.g., a narrower damper opening). In this regard, the FFU tends to be more efficient in delivering airflow per power demand at a higher airflow speed.

Energy performance of an FFU was consistently associated with the pressure rise across the unit as well as the airflow speed through the FFU. To quantitatively verify this, we selected the pressure rise at a certain level—125 Pa to calculate the EPI and the airflow speed, and compare EPI values.

Additionally, Fig. 6 shows the EPI values of the seven large FFUs at a pressure rise of 125 Pa (or about 0.5 in water). The median value of performance index under this condition is identified as 8.3 W per m^3/min (or 0.23 W/cfm). This was lower than the median EPI value reported for the ten smaller units under the same pressure-rise condition, which was 11.3 W per m^3/min (or 0.32 W/cfm) reported in a previous study [9].

Overall, the differences among the unit's EPI values can be many times as much under a same operating condition. This indicates that there is potential for many of the FFU suppliers to improve FFU energy performance. It also indicates that there is an opportunity for users to select more efficient units and specify optimal operating conditions as a means of improving the performance of their cleanroom systems.

6. Conclusions and recommendations

Laboratory testing of FFU energy performance can provide useful data for suppliers and end users to understand the performance of FFU products. The recommended energy metrics include TPE and EPI, as they corresponded to operating conditions—airflow speed and pressure rise across the units. This study analyzes the results from the performance tests conducted when the speed control dial used for adjusting fan-wheel speeds in each FFU was set at its maximum. Performance information produced in this manner allows direct comparison of the units' energy performance under selected operating conditions. Appropriate interpretation and use of this information can suggest good practices and strategically create energy-saving opportunities in FFU applications.

From the sample FFUs tested in this study, there were wide variations of energy and aerodynamics performance among the 122-cm × 122-cm (4-ft × 4-ft) units at given operating conditions:

(1) The median value of TPE of the 122-cm × 122-cm (4-ft × 4-ft) units was higher than their smaller 122-cm × 61-cm (4-ft × 2-ft) counterparts, corresponding to a lower median value of EPI of the 122-cm × 122-cm (4-ft × 4-ft) units under a same operating condition (e.g., 125-Pa pressure rise across the units). This indicates that higher energy efficiency tended to be associated with the larger units.
(2) On the other hand, worse performers among the larger, 122-cm × 122-cm (4-ft × 4-ft) units showed few or no advantage in energy and aerodynamic performance over some of the better, smaller, 122-cm × 61-cm (4-ft × 2-ft) units. This indicates that FFUs with larger sizes alone did not necessarily yield better energy efficiency, and that there were additional factors affecting the actual energy performance of the units beyond the physical size of the unit, motor and fan.
(3) The energy and aerodynamic performance of the 122-cm × 122-cm (4-ft × 4-ft) units can differ significantly at various operating conditions. Some of the units exhibited an even narrower operating range in terms of airflow speed. This indicates that the performance of these large units could be more sensitive to variations in the actual airflow speeds; therefore, it is very critical to

specify, select, and control actual operating range for such units in cleanroom and minienvironment applications.

A standard testing method is needed in order to better understand FFU performance and to be able to make meaningful comparisons. Recommendations for future work include investigating the effect of testing configurations on the performance metrics and improving the robustness of the testing method. Further investigations may also include a list of factors contributing to actual units' performance levels, such as motor types, fan wheels, size, design of unit's interior housing, orientations, and opportunities in design, operation, and control to improve FFUs' overall performance.

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